Ar-Ar dating of Martian meteorite, Dhofar 378: An Early Shock Event?

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Introduction: Martian meteorite, Dhofar 378 (Dho378) is a basaltic shergottite from Oman, weighing 15 g, and possessing a black fusion crust [1]. Chemical similarities between Dho378 and the Los Angeles 001 shergottite suggests that they might have derived from the same Mars locale. The plagioclase in other shergottites has been converted to maskelenite by shock, but Dho378 apparently experienced even more intense shock heating, estimated at 55-75 GPa [2]. Dho378 feldspar (~43 modal %) melted, partially flowed and vesiculated, and then partially recrystallized [3]. Areas of feldspathic glass are appreciably enriched in K, whereas individual plagioclases show a range in the Or/An ratio of ~ 0.18-0.017 [2], [3].

Radiometric dating of martian shergottites indicate variable formation times of ~160-475 Myr, whereas cosmic ray exposure (CRE) ages of shergottites indicate most were ejected from Mars within the past few Myr (e.g., [4]). Most determined ^{39}Ar-^{40}Ar "ages" of shergottites appear older than other radiometric ages because of the presence of large amounts of martian atmosphere or interior ^{40}Ar [5]. Among all types of meteorites and returned lunar rocks, the impact event that initiated the CRE age very rarely reset the Ar-Ar age. This is because a minimum time and temperature is required to facilitate Ar diffusion loss. It is generally assumed that the shock-texture characteristics in martian meteorites were produced by the impact events that ejected the rocks from Mars, although the time of these shock events (as opposed to CRE ages) are not directly dated.

Here we report ^{39}Ar-^{40}Ar dating of Dho378 plagioclase. We suggest that the determined age dates the intense shock heating event this meteorite experienced, but that it was not the impact that initiated the CRE age.

Ar-Ar Results: The ^{39}Ar-^{40}Ar ages and K/Ca ratios for 16 stepwise temperature extractions of a 2.8 mg sample of Dho378 plagioclase are shown in Fig. 1, as a function of cumulative release of ^{39}Ar. The first extraction released significant terrestrial Ar, and these age data are not further considered. Changes in the K/Ca ratio and in the differential rate of ^{39}Ar release with extraction temperature suggest three distinct, but overlapping Ar diffusion domains, which, expressed as cumulative ^{39}Ar release, are: <13%, 13-45%, and >45%. Based on compositional data of [2] we tentatively identify these three phases as rhyolitic glass, milky glass (both part of the mesostasis), and plagioclase glass with crystallized rims. The youngest Ar-Ar age, ~162-165 Myr observed at ~28-40% ^{39}Ar release, is

similar to the Sm-Nd age of 157 ±24 Myr [6]. Other extractions (of the plag.) suggest older Ar-Ar ages and indicate release of trapped martian ^{40}Ar.
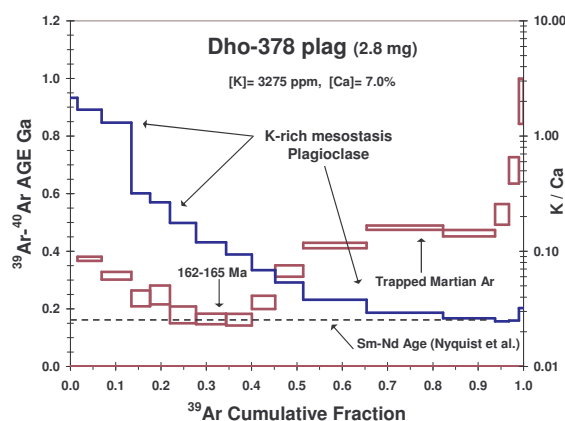

Fig. 1. ^{40}Ar-^{39}Ar ages and K/Ca ratios as a function of ^{39}Ar released during stepwise degassing of Dho378 plagioclase.

To separate trapped ^{40}Ar from ^{40}Ar resulting from in situ decay of ^{40}K, we utilize isochron plots of $^{40}Ar/^{36}Ar$ vs. $^{39}Ar/^{36}Ar$, for which the Ar-Ar age is proportional to the isochron slope. Because Ar components with different compositions appear to be present for extractions releasing <45% of the ^{39}Ar and those releasing >45% of the ^{39}Ar, we examine these two data sets in separate isochron plots. Further, for an isochron plot to represent a linear mixing relationship between two components, ^{40}Ar from in situ decay and a trapped Ar component, cosmogenic ^{36}Ar must be subtracted from the total ^{36}Ar. To do this we use the measured $^{36}Ar/^{37}Ar$ ratio and assume specific values of this ratio produced by nuclear processes. (^{37}Ar is produced in the reactor from Ca; cos-^{36}Ar is produced in space from Ca; and this nuclear ratio is expected to remain approximately constant during Ar extraction.) Trapped ^{36}Ar for each extraction is obtained by subtracting the abundance of $^{36}Ar_{cos}$ from total ^{36}Ar. We adopted three values of nuclear-$(^{36}Ar/^{37}Ar)$ to make this correction. First the minimum measured $^{36}Ar/^{37}Ar$ is taken as an upper limit to $(^{36}Ar/^{37}Ar)_{nuclear}$. Secondly, we used the abundance of $^{36}Ar_{cos}$ measured in an unirradiated sample of Dho378 plag. [7] to determine $(^{36}Ar/^{37}Ar)_{nuclear}$. Thirdly, we assumed a $^{36}Ar_{cos}$ only one-half as large as that directly measured.

The isochron plot for 8 extractions, releasing 3-45% of the ^{39}Ar and corrected for $^{36}Ar_{cos}$ using directly measured $^{36}Ar_{cos}$, is shown in Fig. 2. The Ar-Ar age corresponding to this isochron is 143±4 Myr (where the ± ignores the uncertainty in applying a correction for $^{36}Ar_{cos}$). Applying a

correction assuming only one-half of the measured $^{36}Ar_{cos}$ gives an age of 159 ±2 Myr. Using the minimum measured $^{36}Ar/^{37}Ar$ to apply the correction gives a minimum possible age of 138±5 Myr. All of these ages are within combined uncertainties of the Sm-Nd age [6]. The trapped $^{40}Ar/^{36}Ar$ ratio obtained from the isochron is largely defined by the highest [K] data. The intercepts corresponding to these three $^{36}Ar_{cos}$ corrections are 146 ±16, 150±15, and 119±21, respectively.
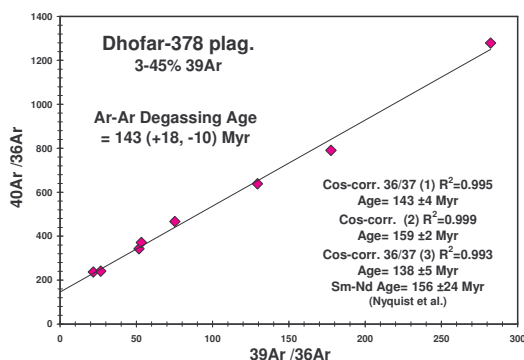
Fig. 2. Trapped $^{40}Ar/^{36}Ar$ ratios against $^{39}Ar/^{36}Ar$ for Dho378 plagioclase.

The isochron plot for extractions releasing 45-98% of the ^{39}Ar scatter considerably and do not define an isochron using any of these applied corrections for $^{36}Ar_{cos}$. These data cannot represent both a constant age and a constant trapped $^{40}Ar/^{36}Ar$ ratio. One of these parameters, or both, must be variable in these extractions.

Ar-Ar Age Interpretation: To interpret the Ar-Ar age results for Dho378 plag. we must consider differences in Ar diffusion characteristics of the two Ar "components" discussed above (<45% and >45% ^{39}Ar). From the release of ^{39}Ar as a function of temperature we calculated the diffusion parameter, D/a^2, and examined these in an Arrhenius plot (Fig. 3). The first ~45% of the ^{39}Ar released shows much greater ease of diffusion loss compared to the last ~55% of the ^{39}Ar released, and the first ~13% of the ^{39}Ar release, which occurred from the high-K glass phase, appears to diffuse even more readily. This finding is consistent, during shock heating, with much greater retention of trapped martian ^{40}Ar in the plagioclase releasing at highest temperature, where Ar diffusion is more difficult, compared to the melted mesostasis material.

We used these diffusion data in a thermal model that compares the cooling rate of bodies of given sizes with various fractional losses of Ar by diffusion [8]. The Ar-Ar isochron (Fig. 2) suggests that no more than ~10% of the ^{40}Ar that accumulated after the degassing event ~143 Myr ago could have been lost in the ~3 Myr CRE initiation event. If we assume Dho378 was 10 cm in diameter when ejected into space, this thermal
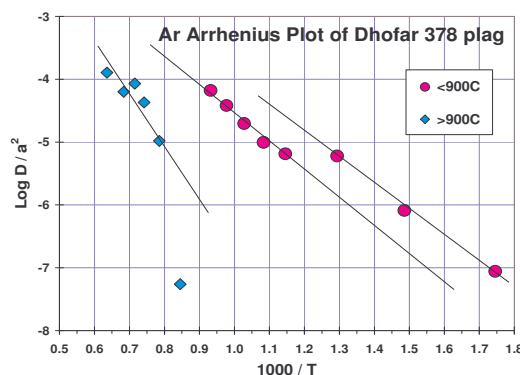
Fig. 3. Arrhenius plot of diffusion parameter D/α^2 vs. reciprocal temperature (in Kelvin) of Dho378. ^{39}Ar diffusion has two distinct phase at the temperature of 900 °C.

model and Fig. 3 imply that the low-temperature "phases" (those releasing <45% of the ^{39}Ar) could not have been heated above ~500°C. Yet, the plagioclase texture implies heating to 1000-1100°C, and the mesostasis apparently melted [2, 3, 9]. If we use the value of D/a^2 at a temperature of 1000°C implied by Fig. 3 (~2x10^{-4}) and examine this in our thermal model, we conclude that to retain ~90% of the ^{40}Ar in the low-temperature phase during heating to 1000°C ~3 Myr ago, Dhofar378 would have to substantially cool in a time of seconds.

Conclusion: We suggest that the ~143 Myr Ar-Ar age determined from the Dho378 isochron may not date the impact that ejected the meteorite into space ~3 Myr ago, but a much earlier impact at ~143 Myr. The relationship between the similar Ar-Ar and Sm-Nd ages is not clear. For the Ar-Ar isochron not to have been reset ~3 Myr ago would require one of two conditions. Either the mesostasis yielding the Ar-Ar age was not heated above ~500°C, in spite of the observation that plagioclase was melted, or alternatively, those K-rich phases heated to melting cooled so rapidly, on the order of seconds over distances of mm, such that ^{40}Ar diffusive loss did not occur. This last explanation would require that pyroxene was not significantly shock-heated.

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